第四章

4.1 (1) 由于三台单相变压器结构、参数相同，当初级接三相对称点压次级空载时，初级绕组中流过对称三相空载电流，产生三相对称磁通，这时初、次级绕组中的感应电动势三相对称，相应的初、次级绕组的相电压和线电压均对称。

（2）当次级届三相对称负载时，次级绕组中流过对称三相电流；初级流过的电流也是三相对称的，因仅有对称电流和对称的三相磁通，所以绕组中的压降和感应电动势也是三相对称的，对应的初、次级的相电压和线电压也均对称。

（3）当次级 a 相接电阻性负载 $r_{L*}=1$，b、c 空载时，变压器单相运行，设$\dot{U}_{A1*}=1+j0$，各量正方向按变压器惯例，得单相负载电流

$$-\dot{I}_{*}=\frac{3\dot{U}_{A1*}}{3Z_{L*}+2Z_{K*}+Z_{2*}+Z_{m0*}}$$

式中

$$Z_{K*}=u_{K*}=0.05$$

$$r_{K*}=u_{a*}=0.02$$

$$x_{K*}=\sqrt{Z_{K*}{}^{2}-r_{K*}{}^{2}}=\sqrt{0.05^{2}-0.02^{2}}=0.0458$$

因为是三相变压器组，所以

$$Z_{2}+Z_{m0}=Z_{m}$$

$$Z_{m*}=\frac{U_{*}}{I_{0*}}=\frac{1}{0.05}=20$$

$$r_{m*}=\frac{P_{0*}}{I_{0*}^{2}}=\frac{0.01}{0.05^{2}}=4$$

$$x_{m*}=\sqrt{Z_{m*}{}^{2}-r_{m*}{}^{2}}=\sqrt{20^{2}-4^{2}}=19.6$$

负载电流 $$-\dot{I}_{*}=\frac{3\times1}{3\times1+2(0.02+j0.0458)+4+j19.6}$$

$$=0.143\angle-70.3^{0}$$

各项电流为

次级 $$\dot{I}_{a*}=\dot{I}_{*}=0.143\angle109.7^{0}$$

$$\dot{I}_{b*}=\dot{I}_{c*}=0$$

初级 $$\dot{I}_{A*}=-\frac{2}{3}\dot{I}_{*}=0.095\angle-70.3^{0}$$

$$\dot{I}_{B*}=\frac{1}{3}\dot{I}_{*}=0.0477\angle 109.7^{0}$$

$$\dot{I}_{C*}=\frac{1}{3}\dot{I}_{*}=0.0477\angle 109.7^{0}$$

a 相电压 $$-\dot{U}_{a*}=\dot{U}_{A1*}+\dot{I}_{a1*}Z_{K*}+\dot{I}_{a2*}Z_{K*}+\dot{I}_{a0*}(Z_{2*}+Z_{m0*})$$

或 $$-\dot{U}_{a*}=-\dot{I}_{*}Z_{L*}=0.143\angle -70.3^{0}=\dot{U}_{A*}$$

b 相电压 $$-\dot{U}_{b*}=\dot{U}_{B1*}+\dot{I}_{b1*}Z_{K*}+\dot{I}_{b2*}Z_{K*}+\dot{I}_{b0*}(Z_{2*}+Z_{m0*})$$

或 $$-\dot{U}_{b*}\approx\dot{U}_{B1*}+\dot{I}_{b0*}(Z_{2*}+Z_{m0*})$$

$$=-\frac{1}{2}-j\frac{\sqrt{3}}{2}+\frac{1}{3}\times 0.143\angle 109.7^{0}(4+j19.6)$$

$$=-1.447-j1.0=1.758\angle -145.35^{0}=\dot{U}_{B*}$$

c 相电压 $$-\dot{U}_{c*}=\dot{U}_{C1*}+\dot{I}_{c1*}Z_{K*}+\dot{I}_{c2*}Z_{K*}+\dot{I}_{c0*}(Z_{2*}+Z_{m0*})$$

或 $$\dot{U}_{c*}\approx\dot{U}_{C1*}+\dot{I}_{c0*}(Z_{2*}+Z_{m0*})$$

$$=-\frac{1}{2}+j\frac{\sqrt{3}}{2}+\frac{1}{3}\times 0.143\angle 109.7^{0}(4+j19.6)$$

$$=-1.447+j0.731=1.62\angle 153.2^{0}=\dot{U}_{C*}$$

线电压 $$\dot{U}_{AB*}=\dot{U}_{ab*}=\dot{U}_{A*}-\dot{U}_{B*}=0.143\angle -70.3^{0}-1.76\angle -145.3^{0}$$

$$=1.728\angle 30.05^{0}$$

$$\dot{U}_{BC*}=\dot{U}_{bc*}=\dot{U}_{B*}-\dot{U}_{C*}=-1.447-j1.0+1.447-j0.731$$

$$=1.731\angle -90^{0}$$

$$\dot{U}_{CA*}=\dot{U}_{ca*}=\dot{U}_{C*}-\dot{U}_{A*}=-1.447+j0.731-0.143\angle -70.3^{0}$$

$$=1.728\angle 149.92^{0}$$

由上述结果可看出，由于带了单相负载造成负载相（a 相）电压降低，开路相（b、c 相）电压升高。由于电源电压对称，所以线电压仍是三相对称的。

4.2 利用与上题相同方法求得 $-\dot{I}_{*}=0.979\angle-2.57^{0}$

各相电流为

次级 $\dot{I}_{a*}=\dot{I}_{*}=0.979\angle177.43^{0}$

$\dot{I}_{b*}=\dot{I}_{c*}=0$

初级 $\dot{I}_{A*}=-\dot{I}_{*}=0.979\angle-2.57^{0}$

$\dot{I}_{B*}=\dot{I}_{*}=0.979\angle177.43^{0}$

$\dot{I}_{C*}=0$

a 相电压 $-\dot{U}_{a*}=\dot{U}_{A1*}+\dot{I}_{a1*}Z_{K*}+\dot{I}_{a2*}Z_{K*}+\dot{I}_{a0*}(Z_{2*}+\dfrac{Z_{*}Z_{m0*}}{Z_{*}+Z_{m0*}})$

或 $-\dot{U}_{a*}=-\dot{I}_{*}Z_{L*}=0.979\angle-2.57^{0}=\dot{U}_{A*}$

b 相电压 $-\dot{U}_{b*}=\dot{U}_{B1*}+\dot{I}_{b1*}Z_{K*}+\dot{I}_{b2*}Z_{K*}+\dot{I}_{b0*}(Z_{2*}+\dfrac{Z_{*}Z_{m0*}}{Z_{*}+Z_{m0*}})$

或 $-\dot{U}_{b*}\approx\dot{U}_{B1*}+\dot{I}_{b0*}(Z_{2*}+\dfrac{Z_{*}Z_{m0*}}{Z_{*}+Z_{m0*}})$

$=-\dfrac{1}{2}-j\dfrac{\sqrt{3}}{2}+\dfrac{1}{3}\times0.979\angle-2.57^{0}(4-3.979+j0.045)$

$=-0.507-j0.880=1\angle-120^{0}=\dot{U}_{B*}$

c 相电压 $-\dot{U}_{c*}=\dot{U}_{C1*}+\dot{I}_{c1*}Z_{K*}+\dot{I}_{c2*}Z_{K*}+\dot{I}_{c0*}(Z_{2*}+\dfrac{Z_{*}Z_{m0*}}{Z_{*}+Z_{m0*}})$

或 $\dot{U}_{c*}\approx\dot{U}_{C1*}+\dot{I}_{c0*}(Z_{2*}+\dfrac{Z_{*}Z_{m0*}}{Z_{*}+Z_{m0*}})$

$=-\dfrac{1}{2}+j\dfrac{\sqrt{3}}{2}+\dfrac{1}{3}\times0.979\angle-2.57^{0}(4-3.979+j0.045)$

$=-0.507+j0.852=1\angle120^{0}=\dot{U}_{C*}$

线电压 $\dot{U}_{AB*}=\dot{U}_{ab*}=\dot{U}_{A*}-\dot{U}_{B*}=0.979\angle-2.57^{0}-1\angle-120^{0}$

$$=1.691\angle 29.08^0$$

$$\dot{U}_{BC*}=\dot{U}_{bc*}=\dot{U}_{B*}-\dot{U}_{C*}=1\angle -120^0-1\angle 120^0$$

$$=1.73\angle -90^0$$

$$\dot{U}_{CA*}=\dot{U}_{ca*}=\dot{U}_{C*}-\dot{U}_{A*}=1\angle 120^0-0.979\angle -2.57^0$$

$$=1.736\angle 148.38^0$$

4.3 （a） 按端点条件列出方程

$$\begin{cases}\dot{I}_a=\dot{I}\\ \dot{I}_b=\dot{I}_c=0\\ \dot{U}_a=\dot{I}\ Z_L\end{cases}$$

以 a 相电流为基准求出次级电流的对称分量

$$\begin{cases}\dot{I}_{a+}=\frac{1}{3}(\dot{I}_a+a\dot{I}_b+a^2\dot{I}_c)=\frac{1}{3}\dot{I}\\ \dot{I}_{a-}=\frac{1}{3}(\dot{I}_a+a^2\dot{I}_b+a\dot{I}_c)=\frac{1}{3}\dot{I}\\ \dot{I}_{a0}=\frac{1}{3}(\dot{I}_a+\dot{I}_b+\dot{I}_c)=\frac{1}{3}\dot{I}\end{cases}$$

得初级电流为

$$\begin{cases}\dot{I}_A=\dot{I}_{A+}+\dot{I}_{A-}+\dot{I}_{A0}=-\frac{1}{k}(\dot{I}_{a+}+\dot{I}_{a-}+\dot{I}_{a0})=-\frac{1}{2}A\\ \dot{I}_B=\dot{I}_{B+}+\dot{I}_{B-}+\dot{I}_{B0}=-\frac{1}{k}(a^2\dot{I}_{a+}+a\dot{I}_{a-}+\dot{I}_{a0})=0\\ \dot{I}_C=\dot{I}_{C+}+\dot{I}_{C-}+\dot{I}_{C0}=-\frac{1}{k}(a\dot{I}_{a+}+a^2\dot{I}_{a-}+\dot{I}_{a0})=0\end{cases}$$

（b） 按端点条件列出方程

$$\dot{I}_a-\dot{I}_b=\dot{I}$$

$$\dot{I}_b=\dot{I}_c$$

$$\dot{U}_a = \dot{I}\ Z_L$$

以 a 相电流为基准求出次级电流的对称分量

$$\begin{cases} \dot{I}_{a+} = \frac{1}{3}(\dot{I}_a + a\dot{I}_b + a^2\dot{I}_c) = \frac{1}{3}\dot{I} \\ \dot{I}_{a-} = \frac{1}{3}(\dot{I}_a + a^2\dot{I}_b + a\dot{I}_c) = \frac{1}{3}\dot{I} \\ \dot{I}_{a0} = \frac{1}{3}(\dot{I}_a + \dot{I}_b + \dot{I}_c) = 0 \end{cases}$$

初级中无零序电流，得初级电流为

$$\begin{cases} \dot{I}_A = \dot{I}_{A+} + \dot{I}_{A-} = -\frac{1}{k}(\dot{I}_{a+} + \dot{I}_{a-}) = -\frac{1}{3}A \\ \dot{I}_B = \dot{I}_{B+} + \dot{I}_{B-} = -\frac{1}{k}(a^2\dot{I}_{a+} + a\dot{I}_{a-}) = \frac{1}{6}A \\ \dot{I}_C = \dot{I}_{C+} + \dot{I}_{C-} = -\frac{1}{k}(a\dot{I}_{a+} + a^2\dot{I}_{a-}) = \frac{1}{6}A \end{cases}$$

（c） 按端点条件列出方程

$$\dot{I}_a - \dot{I}_c = \dot{I}$$

$$\dot{I}_b = \dot{I}_c$$

$$\dot{U}_a = \dot{I}\ Z_L$$

以 a 相电流为基准求出次级电流的对称分量

$$\begin{cases} \dot{I}_{a+} = \frac{1}{3}(\dot{I}_a + a\dot{I}_b + a^2\dot{I}_c) = \frac{1}{3}\dot{I} \\ \dot{I}_{a-} = \frac{1}{3}(\dot{I}_a + a^2\dot{I}_b + a\dot{I}_c) = \frac{1}{3}\dot{I} \\ \dot{I}_{a0} = \frac{1}{3}(\dot{I}_a + \dot{I}_b + \dot{I}_c) = 0 \end{cases}$$

Dd 联接中无零序电流，处级零序电流为零，得初级相电流为

$$\dot{I}_{AX} = \dot{I}_{AX+} + \dot{I}_{AX-} = -\frac{2}{3k}\dot{I} = -\frac{1}{3}\dot{I}$$

$$\dot{I}_{BY}=\dot{I}_{BY+}+\dot{I}_{BY-}=\frac{1}{3k}\dot{I}=\frac{1}{6}\dot{I}$$

$$\dot{I}_{CZ}=\dot{I}_{CZ+}+\dot{I}_{CZ-}=\frac{1}{3k}\dot{I}=\frac{1}{6}\dot{I}$$

初级线电流为

$$\dot{I}_{A}=\dot{I}_{AX}-\dot{I}_{CZ}=-\frac{1}{3}\dot{I}-\frac{1}{6}\dot{I}=-\frac{1}{2}\dot{I}=-\frac{1}{2}A$$

$$\dot{I}_{B}=\dot{I}_{BY}-\dot{I}_{AX}=\frac{1}{6}\dot{I}-(-\frac{1}{3}\dot{I})=\frac{1}{2}\dot{I}=\frac{1}{2}A$$

$$\dot{I}_{C}=\dot{I}_{CZ}-\dot{I}_{BY}=\frac{1}{6}\dot{I}-\frac{1}{6}\dot{I}=-\frac{1}{2}\dot{I}=0$$

（d） 按端点条件列出方程

$$\dot{I}_{a}=\dot{I}$$

$$\dot{I}_{b}=\dot{I}_{c}=0$$

$$\dot{U}_{a}=\dot{I}\ Z_{L}$$

以 a 相电流为基准求出次级电流的对称分量

$$\begin{cases}\dot{I}_{a+}=\frac{1}{3}(\dot{I}_{a}+a\dot{I}_{b}+a^{2}\dot{I}_{c})=\frac{1}{3}\dot{I}\\ \dot{I}_{a-}=\frac{1}{3}(\dot{I}_{a}+a^{2}\dot{I}_{b}+a\dot{I}_{c})=\frac{1}{3}\dot{I}\\ \dot{I}_{a0}=\frac{1}{3}(\dot{I}_{a}+\dot{I}_{b}+\dot{I}_{c})=\frac{1}{3}\dot{I}\end{cases}$$

Dd 联接中无零序电流，处级零序电流为零，得初级相电流为

$$\dot{I}_{AX}=\dot{I}_{AX+}+\dot{I}_{AX-}=-\frac{2}{3k}\dot{I}=-\frac{1}{3}\dot{I}$$

$$\dot{I}_{BY}=\dot{I}_{BY+}+\dot{I}_{BY-}=\frac{1}{3k}\dot{I}=\frac{1}{6}\dot{I}$$

$$\dot{I}_{CZ}=\dot{I}_{CZ+}+\dot{I}_{CZ-}=\frac{1}{3k}\dot{I}=\frac{1}{6}\dot{I}$$

初级线电流为

$$\dot{I}_A = \dot{I}_{AX} - \dot{I}_{BY} = -\frac{1}{3}\dot{I} - \frac{1}{6}\dot{I} = -\frac{1}{2}\dot{I} = -\frac{1}{2}A$$

$$\dot{I}_B = \dot{I}_{BY} - \dot{I}_{CZ} = \frac{1}{6}\dot{I} - \frac{1}{6}\dot{I} = 0$$

$$\dot{I}_C = \dot{I}_{CZ} - \dot{I}_{AX} = \frac{1}{6}\dot{I} - (-\frac{1}{3}\dot{I}) = \frac{1}{2}\dot{I} = \frac{1}{2}A$$